

## SPECIFICATION

TO ALL WHOM IT MAY CONCERN:

BE IT KNOWN THAT WE, Kazuya Takemoto, a citizen of Japan residing at Kawasaki, Japan, Tatsuya Usuki, a citizen of Japan residing at Kawasaki, Japan and Motomu Takatsu, a citizen of Japan residing at Kawasaki, Japan have invented certain new and useful improvements in

### SINGLE-PHOTON GENERATOR AND SINGLE- PHOTON GENERATING METHOD

Of which the following is a specification:-

TITLE OF THE INVENTION

SINGLE-PHOTON GENERATOR AND SINGLE-PHOTON  
GENERATING METHOD

5 CROSS-REFERENCE TO RELATED APPLICATION

The present application is based on Japanese  
priority application No.2003-043188 filed on February  
20, 2003, the entire contents of which are hereby  
incorporated by reference.

10

BACKGROUND OF THE INVENTION

The present invention generally relates to  
optical sources, and more particularly to a single-  
photon generator and single-photon generation method.

15

Safe and secure cryptographic  
telecommunication is indispensable technology for  
realizing the next generation information society  
including electronic government, electronic commerce,  
and the like.

20

Currently, the RSA public key cryptosystem  
is used extensively in the Internet for providing  
security on communications exchanged through the  
Internet. According to the RSA public key cryptosystem,  
the security is provided solely on the principle of  
25 difficulty of calculating the factorization of  
polynomials into prime numbers and thus relies on the  
difficulty of conducting huge amount of calculation in  
a practical time. This means, on the other hand, that  
when a quantum computer, capable of conducting  
30 parallel processing at enormously high speed is  
realized, the time needed for decrypting a code is  
shortened drastically, and it is no longer possible to  
prevent copying, such as wiretapping or falsification,  
of data by a third party when public key cryptosystem  
35 is used.

Quantum cryptography is expected to provide  
solution to this problem of security.

In quantum cryptography, information is transmitted not in the form of conventional aggregate or bunch of photons but in the form of single photons.

In the case one bit of information is  
5 imparted to a single photon in the form of polarization information, for example, the information thus given to each photon complies with the uncertainty principle and no-cloning theorem, and because of this, it becomes no longer possible to take  
10 out the bit information without destroying the state of the photon. Thus, in the case a third party has conducted copying or falsification of the information in the communication path, such a conduct is detected immediately.

15 Thus, in the case of using quantum cryptography, the security of cryptographic key shared between two parties is guaranteed by the physical principle, not by the quantity of calculation, as long as a single photon is used for the carrier of the  
20 information. On the other hand, in order to secure the security of such a cryptographic key and to eliminate the risk of wiretapping, it is necessary to provide a highly reliably single-photon source.

In a conventional quantum cryptography  
25 experiment, a diminished laser beam pulse has been used as a quasi-single-photon source (Rev. Mod. Phys., vol. 74, 145 (2002)). With this technology, the probability of existence of photons is reduced to the level of about 1 photon per 10 pulses in average, by  
30 diminishing the laser beam power by using an attenuator. In this technology, it becomes possible to achieve various advantages such as simple system setup, capability of changing the wavelength, capability of operation at room temperature, and the like.

35 In this conventional technology, on the other hand, because of the fact that the timing of emission of single photon complies with the Poisson

distribution, there can arise the situations with finite probability that no photon emission occurs at all or several photons are emitted simultaneously. Thus, such a conventional system has a drawback in  
5 that efficiency of photoemission is poor. Further, such a conventional system has a problem of vulnerability to attack by a third party. More specifically, the aforementioned security of quantum cryptography is guaranteed only for the case in which  
10 there occurs single-photon emission, as noted previously. This security pertinent to the quantum cryptography vanishes when there are formed several photons simultaneously.

There are known mechanisms of single-photon  
15 generation that use the principles different from the one that attenuates a laser beam.

For example, Kim, et al., reports a single-photon turn-style device that generates a single photon for each external modulation electric field, by  
20 using the effect of Coulomb blockade occurring at a pn junction of semiconductor (Nature, vol. 397, 500 (1999)). Further, Lounis et al., report that single photons can be generated with repetition of 6.25MHz at the maximum, by embedding molecules of terrylene into  
25 a thin film of p-terphenyl (Nature, vol. 407, 491 (2000)).

However, the former proposal has a drawback in that the operational temperature is extremely low (50mK), and there arises a problem associated with  
30 this that unnecessary photons are formed by the background current. In the latter proposal, on the other hand, p-terphenyl in the matrix produces unnecessary photons. Thus, none of these conventional proposals could provide the solution leading to  
35 practical quantum cryptography device.

It should be noted that next two requirements are imposed for a single-photon optical

source used for a quantum cryptography device.

① There should occur no simultaneous emission of plural photons (anti-bunching)

② Capability of emitting a single photon  
5 with desired timing (photon on-demand)

Conventionally, there have been problems in any of ① and ② or in both of these. If the requirement ① is not satisfied, there would occur increase in the probability of overlooking wiretapping.  
10 When the requirement ② is not satisfied, on the other hand, the error at the reception side is increased and sufficient bit rate is not achieved.

#### SUMMARY OF THE INVENTION

15 Accordingly, it is a general object of the present invention to provide a novel and useful optical source wherein the foregoing problems are eliminated.

Another and more specific object of the  
20 present invention is to provide a single-photon generator satisfying the foregoing conditions simultaneously and a single photon formation method.

Another object of the present invention is to provide a single-photon generator, comprising:  
25 an exciton generation part including therein a quantum dot;

an excitation part for generating an exciton in said exciton generation part;

a recombination control part for controlling  
30 recombination timing of said exciton in said exciton generation part; and

an optical window provided in said exciton generation part so as to pass a single photon formed as a result of recombination of said exciton,

35 said recombination control part causing, in said exciton generation part, recombination of said exciton at longer intervals than a recombination

lifetime of a exciton molecule.

Another object of the present invention is to provide a single-photon generating method, comprising the steps of:

- 5           forming an exciton in a medium; and  
          generating a single photon by causing recombination in said exciton,  
          said recombination step being conducted with an interval longer than a recombination lifetime of a  
10   exciton molecule in said medium.

The present invention relies on the principle that the recombination lifetime of an exciton that produces a single photon as a result of recombination is longer than the recombination  
15   lifetime of an exciton molecule (biexciton) that produces a plurality of photons as a result of the recombination.

Thus, according to the present invention, it becomes possible to extract a single photon with  
20   reliability at the time of generating a single photon in a medium that constitutes the exciton generation part as a result of recombination of the exciton thus excited, by conducting the recombination of the exciton with such a timing that that the recombination  
25   of the exciton molecules excited simultaneously in the medium is over. It should be noted that such an exciton can be formed easily by causing optical excitation in a quantum dot, particularly the quantum dot forming a heterojunction of type II.

30           Thus, according to the present invention, it becomes possible to extract a single photon with reliability at the time of generating a single photon by the recombination of an exciton excited in the medium that forms the exciton generation part, by  
35   causing the recombination of the exciton with such a timing that the recombination of the exciton molecules excited simultaneously in the medium is over. It

should be noted that such an exciton can be formed easily by optical excitation in a quantum dot, particularly in the quantum dot forming a heterojunction of type II. By using the single-photon generator and the single-photon generation method of the present invention, it becomes possible to realize a long distance communication system capable of conducting secure and reliable key delivery.

Other objects and further features of the present invention will become apparent from the following detailed description when read in conjunction with the attached drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a diagram showing the construction of a single-photon generator according to a first embodiment of the present invention;

Figure 2 is a diagram showing a part of the single-photon generator of Figure 1 with an enlarged scale;

Figures 3A and 3B are diagrams explaining the principle of the single-photon generator of Figure 1;

Figure 4 is a diagram showing the distribution of exciton molecules formed in a single quantum dot in the single-photon generator of Figure 1;

Figures 5A - 5D are diagrams explaining the operation of the single-photon generator of Figure 1;

Figure 6 is a diagram explaining the preparation method of the quantum dot according to a second embodiment of the present invention; and

Figure 7 is a diagram showing the band structure of the quantum dot of Figure 6.

#### DETAILED DESCRIPTION OF THE INVENTION

[FIRST EMBODIMENT]

Figure 1 shows the construction of a single-photon generator 10 according to a first embodiment of the present invention.

Referring to Figure 1, the single-photon  
5 generator 10 includes an undoped AlAs barrier layer 12  
formed epitaxially on an n-type GaAs substrate 11 with  
a thickness of 20 - 30nm, and quantum dots 13 of an  
InAs-GaSb system are formed with a large number on the  
AlAs barrier layer 12 with the S-K (Stranski-  
10 Krastanow) mode growth mechanism to be explained  
later.

As shown in Figure 2, each of the quantum  
dots 13 has a compositional gradient therein, and thus  
has a compositional profile, such that the inside of  
15 the quantum dot is enriched with InAs and the outside  
of the quantum dot is enriched with GaSb.

Further, another undoped AlAs barrier layer  
14 of about 20 - 30nm in the thickness is formed  
epitaxially on the barrier layer 12 so as to bury the  
20 quantum dot 13, and a p-type GaAs contact layer 15 of  
about 20nm thickness is formed epitaxially on the  
barrier layer 14.

On the contact layer, an upper electrode 16  
having an optical window 16A in correspondence to one  
25 of the plural quantum dots 13 is provided in ohmic  
contact therewith, such that the optical window 16A is  
located immediately above the foregoing quantum dot,  
and a lower electrode 17 is formed on the bottom  
surface of the GaAs substrate 11 in ohmic contact  
30 therewith.

The single-photon generator 10 of Figure 1  
further includes a laser diode 18 having an  
oscillation wavelength of 800nm - 1 $\mu$ m provided so as  
to illuminate the quantum dot 13, wherein the laser  
35 diode 18 causes excitation of excitons by emitting a  
laser beam 18A to the quantum dot 13 as will be  
explained with reference to Figure 3A.



Further, the single-photon generator 10 of Figure 1 includes a bias power supply 19 connected between the electrodes 16 and 17 through a switch circuit 19A, and a reverse bias voltage is applied to the electrodes 16 and 17 from the bias power supply 19 when the switch circuit 19A is closed under control of the control circuit 19B.

Figure 3A shows the band diagram of the quantum dot 13 of Figure 1 in an unbiased state.

Referring to Figure 3A, an electron 1 and a hole 2 are excited in the quantum dot 13 when an excitation optical pulse having a wavelength  $\nu$  corresponding to the bandgap of the quantum dot 13 comes in to the quantum dot 13. Because the conduction band  $E_c$  and the valence band  $E_v$  are inclined in the quantum dot 13 in correspondence to the compositional gradation explained previously, the electron thus excited is held in the lower end part of the quantum dot 13 enriched with InAs while the hole is held in the upper end part of the quantum dot 13 enriched with GaSb. Thereby, the electron and the hole are separated spatially as shown in the arrow in the drawing. Thus, the electron and hole are held in a polarized state and form an exciton. Because there is little overlapping of wavefunction between the electron and the hole, such an exciton is stable, and a recombination lifetime reaching 1.7 - 1.8 nanoseconds is achieved.

When the switch 19A is closed as shown in Figure 3B, on the other hand, and a reverse bias voltage is applied between the electrode 16 and 17, and the band in the quantum dot 13 is flattened by the effect of the applied electric field. Thereby, the polarization or localization of the electron 1 and the hole 2 shown in Figure 3A vanishes. In this case, an overlap is caused in the wavefunction of the electron and the wavefunction of the hole, and the electron 1

and the hole 2 cause recombination easily in the quantum dot 13. As a result of such a recombination, a single photon 3 is emitted.

The single photon thus formed exits through  
5 the optical window 16A in the electrode 16 as shown in Figure 1 and is gated by an optical gate member 20 such as an acousto-optic device, which is controlled in synchronization with the switch circuit 19A by a control unit 19B. The single photon thus obtained is  
10 supplied to a quantum computer not illustrated.

In the excitation process that uses the laser 18 of Figure 3A, there are cases in which plural electrons and holes are excited by the irradiation of the excitation optical beam, and thus, it is generally  
15 inevitable that there occurs formation of exciton molecules (exciton molecules) in addition to the exciton. In the case of such a exciton molecule, on the other hand, the degree of spatial separation of electron and hole is small as compared with the case  
20 of exciton shown in Figure 3A, as schematically shown in Figure 4, and thus, the electron and hole in the exciton molecule are annihilated efficiently in short time by causing recombination, typically within several hundred picoseconds, after the excitation. In  
25 the case of the exciton, the spatial separation between the electron and hole is large as explained before and a recombination lifetime of about 1.7 - 1.8 nanoseconds, which is longer than the recombination lifetime of a exciton molecule, is achieved.

30 Thus, in the single-photon generator 10 of Figure 1, it becomes possible to produce only one single photon with reliability by constructing the control unit 19B such that the control unit 19B drives the switch 19A after the excitation by the laser beam  
35 18A with the timing such that the recombination lifetime of exciton molecule has elapsed. For example, the control unit 19B drives the switch 19A after 1

nanosecond has elapsed after the excitation by the laser beam has been conducted. Thereby; the photons emitted by the recombination of the exciton molecules prior to the emission of the single photon are cut off  
5 successfully by synchronizing the optical gate member 20 with the switch circuit 19A.

For such an optical gate member 20, it is possible to use a high speed optical switching device that uses an electrooptic crystal such as  $\text{KH}_2\text{PO}_4$ ,  
10  $\text{NH}_4\text{H}_2\text{PO}_4$ ,  $\text{LiNbO}_3$ ,  $\text{LiTaO}_3$ , and the like.

In the case the quantum dot 13 is formed by the S-K mode growth process, the distribution of the quantum dots 13 on the AlAs barrier layer 12 generally becomes random. Because the optical window 16A is  
15 formed in the electrode 16 in the single-photon generator 10 of Figure 1 in correspondence to one of the plural quantum dots 13, the photon emission from other quantum dots are blocked by the electrode 16. In other words, the electrode 16 functions also as an  
20 optical mask in the single-photon generator 10 of Figure 1.

Figures 5A - 5D are diagrams explaining the operation of the single-photon generator 10 of Figure 1.

25 Referring to Figures 5A and 5B, there occurs excitation of exciton or exciton molecules in correspondence to each optical pulse in the laser beam 18A produced by the laser diode 18 as shown in Figure 5B, wherein the exciton molecules formed of plural  
30 electrons and holes are annihilated immediately as shown in Figure 5B by a continuous line. On the other hand, the exciton formed of a single electron and a single hole has a long recombination lifetime and remains even after the exciton molecules have  
35 disappeared as shown in Figure 5B by a broken line.

Thus, in the single-photon generator 10 of Figure 1, the control unit 19B drives the switch 19A

with the timing of Figure 5C, and as a result, a single electron is emitted with the timing shown in Figure 5C.

Further, by driving the optical gate member  
5 20 with the timing of Figure 5D in the single-photon generator 10 of Figure 1, it becomes possible to take out only the necessary single photon for use in the external quantum computer, and the like.

10 [SECOND EMBODIMENT]

Next, the method of forming the quantum dot 13 used with the construction of Figure 1 will be explained briefly with reference to Figure 6 as a second embodiment of the present invention.

Referring to Figure 6, a GaAs substrate 11  
15 formed with an AlAs layer 12 epitaxially thereon is introduced into an MBE apparatus and is held to a substrate temperature of 600°C. Further, an InAs layer 13a is formed on the AlAs layer 12 with a thickness of  
20 2 - 3 molecular layers by using molecular beams from an In cell and an As cell held to respective cell temperatures of 850°C and 300°C. Because the InAs layer 13a forms a strained system with respect to the GaAs substrate 11, the In atoms and the As atoms  
25 deposited on the AlAs layer 12 gather together on the surface, and there is formed an island or dot 13a of InAs having a diameter is of about 20nm.

In the present embodiment, a GaSb layer, forming a type II heterojunction to InAs, is formed on  
30 the InAs layer 13a with the thickness of about 15 molecular layers, after the InAs dots 13a are thus formed, by using the molecular beams from a Ga cell and a Sb cell held respectively to the cell temperatures of 950°C and 480°C. In this case, because  
35 of the effect of the lattice strained system explained before, the Ga atoms and the Sb atoms concentrate on the InAs dot 13a, and there is formed a GaSb layer 13b

on the InAs dot 13a. It is known that such an InAs/GaSb dot forms a type II heterojunction in the case the diameter is smaller than  $87\text{\AA}$ . (Phys. Rev. B. vol.48, 4643 (1993)).

5               Figure 7 shows the band diagram of the structure of Figure 6 thus formed.

Referring to Figure 7, it can be seen that there is formed a heterojunction of type II between the InAs dot 13a and the GaSb dot 13b as shown in the  
10 continuous line in the drawing. Thereby, it is believed that there is formed a single dot having a compositional gradation as shown in the drawing by a broken line because of the mixing of elements caused between the GaSb dot 13b and the InAs dot 13a during  
15 the growth of the GaSb dot 13b. Typically, such a dot has a diameter of about 20 - 50nm and a height of about 5 - 10nm and forms the quantum dot 13 in which the carriers are confined in three dimensions.

In the foregoing embodiment, the quantum dot  
20 13 including therein the heterojunction of type II is not limited to the lamination of InAs and GaSb but it is also possible to use a lamination of InGaP and InP or GaAsSb and InP. Furthermore, the substrate 11 is not limited to GaAs but it is also possible to use an  
25 InP substrate or a GaP substrate, provided that it forms a strained system with regard to the quantum dot 13.

Further, the quantum dot 13 can be formed also by using an MOCVD process, in addition to the MBE  
30 process.

Further, the present invention is not limited to the embodiments described heretofore, but various variations and modifications may be made without departing from the scope of the invention.